ARGO: THE GLOBAL ARRAY OF PROFILING FLOATS

The Argo Science Team[1]

ABSTRACT *- A broad-scale global array of temperature/salinity profiling floats, known as Argo, is planned as a major component of the ocean observing system, with deployment scheduled to begin in 2000. Conceptually, Argo builds on the existing upper-ocean thermal networks, extending their spatial and temporal coverage, depth range and accuracy, and enhancing them through addition of salinity and velocity measurements. The name Argo is chosen to emphasize the strong complementary relationship of the global float array with the Jason altimeter mission. For the first time, the physical state of the upper ocean will be systematically measured and assimilated in near real-time.*

Objectives of Argo fall into several categories. Argo will provide a quantitative description of the evolving state of the upper ocean and the patterns of ocean climate variability, including heat and freshwater storage and transport. The data will enhance the value of the Jason altimeter through measurement of subsurface vertical structure (T(z), S(z)) and reference velocity, with sufficient coverage and resolution for interpretation of altimetric sea surface height variability. Argo data will be used for initialization of ocean and coupled forecast models, data assimilation and dynamical model testing. A primary focus of Argo is seasonal to decadal climate variability and predictability, but a wide range of applications for high-quality global ocean analyses is anticipated.

The initial design of the Argo network is based on experience from the present observing system, on newly gained knowledge of variability from the TOPEX/Poseidon altimeter, and on estimated requirements for climate and high-resolution ocean models. Argo will provide 100,000 T/S profiles and reference velocity measurements per year from about 3000 floats distributed over the global oceans at 3-degree spacing. Floats will cycle to 2000 m depth every 10 days, with a 4-5 year lifetime for individual instruments. All Argo data will be publicly available in near real-time via the GTS, and in scientifically quality-controlled form with a few months delay. Global coverage should be achieved during the Global Ocean Data Assimilation Experiment, which together with CLIVAR and GCOS/GOOS, provide the major scientific and operational impetus for Argo. The design emphasizes the need to integrate Argo within the overall framework of the global ocean observing system.

International planning for Argo, including sampling and technical issues, is coordinated by the Argo Science Team. Nations presently having Argo plans that include float procurement or production include Australia, Canada, France, Germany, Japan, the U.K., and the U.S.A., plus a European Union proposal. Combined deployments from these nations may exceed 700 floats per year as early as 2001. Broad participation in Argo by many nations is anticipated and encouraged either through float procurement, logistical support for float deployment, or through analysis and assimilation of Argo data.

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1 - THE GENESIS AND DESIGN OF ARGO

Three recent developments make the deployment of a global array of profiling floats, Argo, a key step for oceanography and climate science.

- First, the availability of precision satellite altimeters, measuring sea surface height globally every 10 days, creates a compelling rationale for *in situ* datasets that are needed to successfully interpret and complement the surface topography.
- Second, development of the profiling float (Fig 1) makes it feasible to observe the physical state of the ocean (temperature, salinity, velocity) on a regular and routine basis anywhere in the world. This is particularly significant because it means that heat and freshwater storage in the global air-sea-land climate system, both of which are dominated by oceanic variability, can be accurately measured for the first time.
- Finally, the maturation of data assimilation capabilities – including developments in both hardware and assimilation techniques – provides a framework to stitch together the subsurface and remotely sensed surface datasets in a dynamically consistent fashion. The data include wind forcing (from scatterometer) as well as the oceanic response - sea level variability and its subsurface counterparts.

With a comprehensive satellite remote sensing system now in place, and the powerful machinery for data assimilation available, the deployment of a global subsurface array becomes a top priority with a wide spectrum of scientific and operational applications.

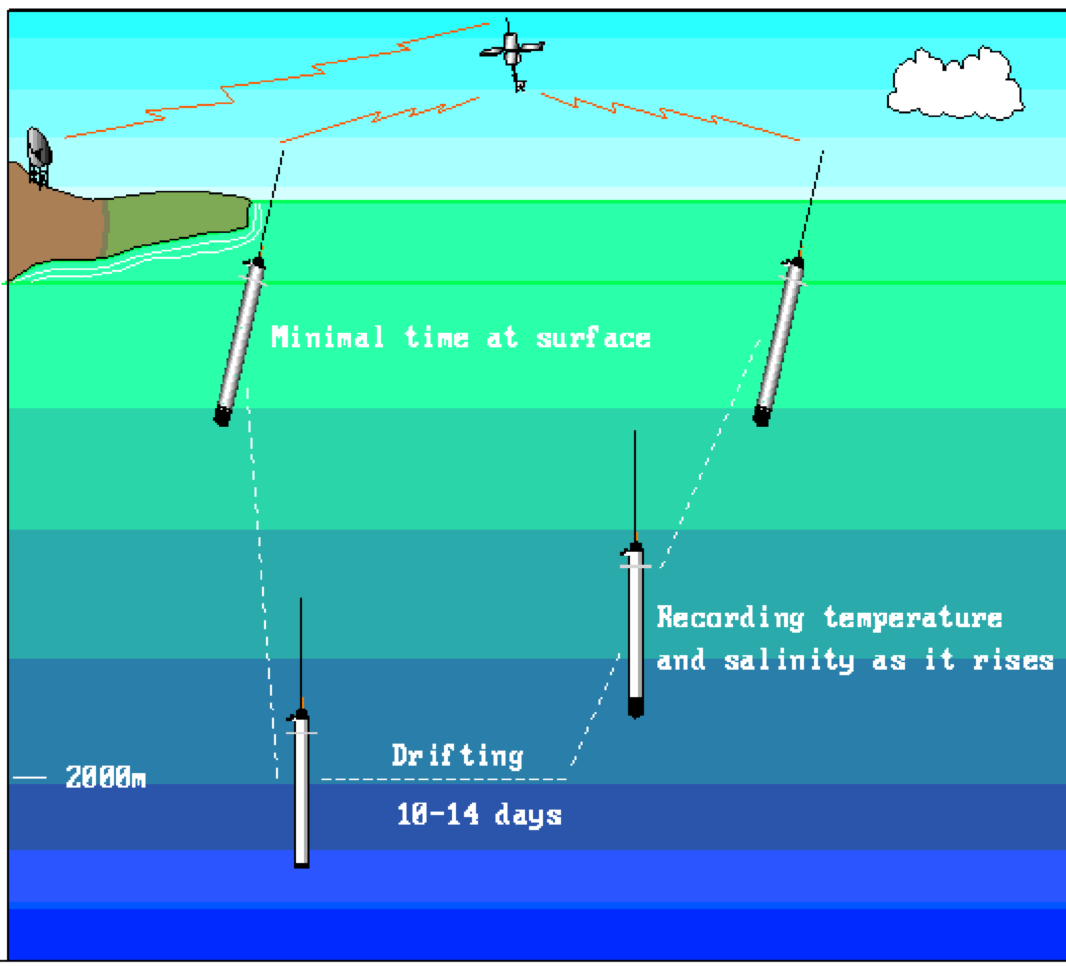

Fig 1: Schematic of a single cycle in the mission of a profiling float. Float lifetime is expected to be about 200 cycles. Note that the parking depth may be shallower than the profiling depth.

It should be emphasized that Argo is not a complete *in situ* observing system. Its purpose is to provide global coverage of the upper ocean on broad spatial scales and on time-scales of months and longer. The array's spatial resolution will not be fine enough to resolve boundary currents nor its time sampling adequate for the equatorial wave-guide. Initially, its domain will be limited to the upper 2000 m. Hence the global float array must be supplemented in ways that are regionally appropriate and dynamically sensible. Argo must knit together the regional enhancements and provide them with a global context. Climate is intrinsically a global problem that cannot be completely addressed with regional measurements.

Having recognized the need for a global subsurface array, the design of Argo is an ongoing exercise in balancing the array's requirements against the practical limitations imposed by technology and resources. A complicating factor is that the statistics of ocean variability are poorly known in many regions, making array design a necessarily iterative process. The Argo Science Team was instructed to view the design question from a variety of different angles. It is reassuring that these varying perspectives provide consistent estimates of what is needed in a global array (Argo Science Team, 1998, 1999). In brief summary, these perspectives are:

(1) Previous and ongoing float studies: A five-year deployment of about 300 floats in the tropical and South Pacific Ocean (Davis, 1998) was found to be adequate for mapping the mean geostrophic pressure field at mid-depth but not its time variability. The domain included nearly half the global ocean. These results showed that a large increase in float density was needed for mapping of time varying fields. Recent experience with profiling floats in the North Atlantic at much higher spatial density emphasizes this finding.

(2) The existing upper ocean thermal network: Numerous network design studies have been carried out, using the XBT datasets to provide necessary statistics, as summarized by White (1995). In approximate terms, an array with spacing of a few hundred kilometers is sufficient to determine heat storage in the surface layer with an accuracy of 10 w/m^2 on seasonal time-scales and over areas 1000 km on a side. This improves to about 3 w/m^2 for interannual fluctuations. Combination of XBT and altimetric data can improve this further.

(3) The altimetric dataset: Spectral analysis of altimetric data shows that on a global basis, half of the variance in sea level is at wavelengths shorter than 1000 km (Wunsch and Stammer, 1995). If the climate signal of interest is defined to include all wavelengths longer than 1000 km, then an array with 500 km spacing provides a 1:1 signal to noise ratio. Spacing of 250 km would improve this ratio by more than a factor of 3. The unresolved variability – fronts, mesoscale eddies etc. - has a short decorrelation time, typically 10-20 days, compared with the seasonal and longer climate signals of interest. Therefore, the signal-to-noise ratio can be increased by temporal or multi-track averaging. As a function of latitude, the half-power point varies from 1300 km wavelength in the tropics to 700 km at 50^{o}N (Stammer, 1997).

(4) Climate signals in WOCE hydrographic data: Decadal variability in the subtropical North Atlantic has been described using comparisons of WOCE hydrographic transects with previous hydrography along the same tracks (Parilla et al, 1994, Joyce and Robbins, 1996). Subsampling experiments show that these basin-scale signals can be recovered by using stations at 3-degree spacing, providing enough independent samples to average out the eddy noise.

(5) Requirements for assimilating models: Initially, these are not distinctly different from the requirements for pure data analysis. The models require sufficient data to determine the statistics linking point measurements to the smoothed fields of the simulations. They also require sufficient data to estimate comparison fields for rigorous testing of model results. While there is still much to be done to determine the optimal datasets for assimilation, it is clear that the requirements remain substantial.

The Argo Science Team concluded that a global array of about 3000 profiling floats with uniform 3° spacing in latitude and longitude is practical and should be the initial target for Argo (Fig 2). With the array specified in this way, the density of floats will be twice as great at 60° latitude as at the equator. This is not as steep an increase with latitude as is indicated using statistics from altimetric sea level. However, a relatively higher signal-to-noise ratio in tropical latitudes is justified given the known importance of climate signals in the tropics. Argo deployments at high latitudes are viewed as more exploratory in nature while those in the tropics are made with a practical view of improving seasonal to interannual prediction.

It is recognized that the design of the Argo array is not static. It will continue to evolve as the scientific requirements are refined and as the array itself provides sufficient statistical information to improve its own design. The instrumentation itself will also continue to evolve. Gains in depth range, energy efficiency and salinity stability are anticipated, plus the development of new sensors and the emergence of glider technology. The latter, providing control over float movements, will enable floats to take on a variety of new missions such as time-series measurements at fixed locations and repeated hydrographic sections. The challenge will be evolve the Argo design in a way that maintains continuity of the basic broad-scale physical measurements while expanding value and applications through regional or global enhancements.

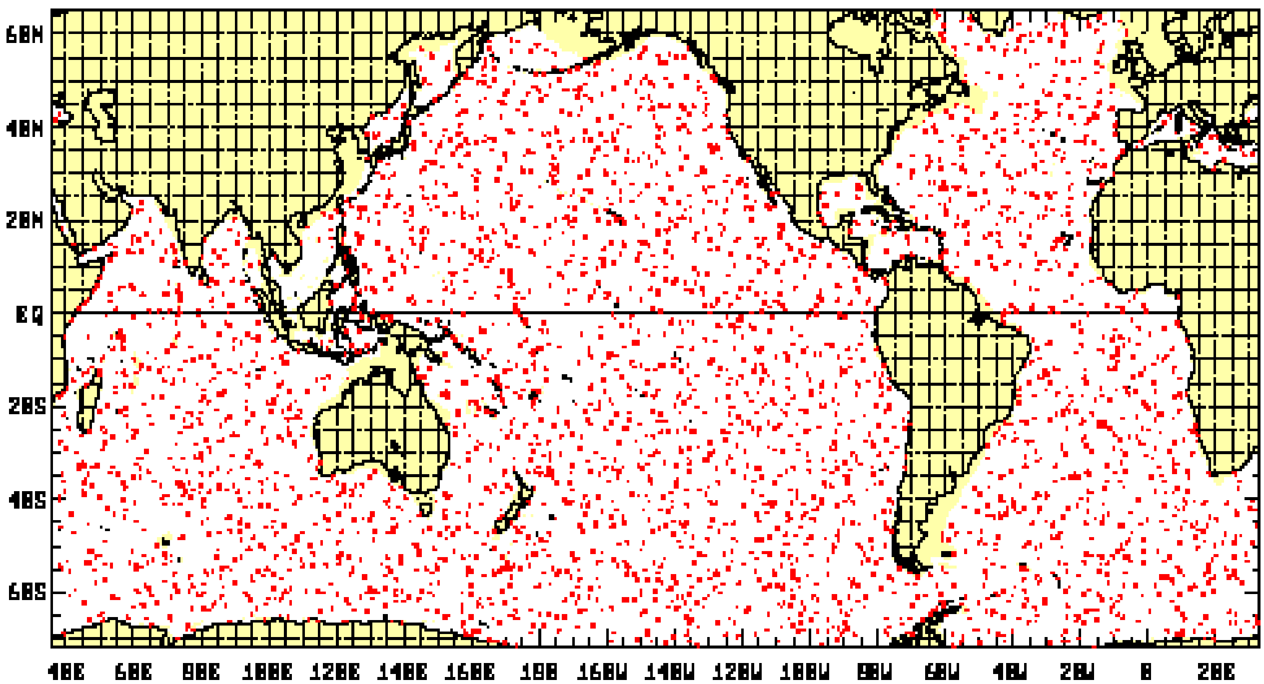

Fig 2: Schematic of the Argo float array. Positions of 3000 mid-depth floats are shown 3 years after deployment at 3° latitude and longitude spacing in the NRL global eddy-resolving model (courtesy H. Hurlburt). The mid-depth flow shows no tendency to produce clumps or gaps.

2 - ANTICIPATING ARGO'S ACHIEVEMENTS

Argo is conceptually an extension of today's upper ocean thermal networks. Some of its achievements can be anticipated by extrapolating from the present capabilities to more comprehensively sampled global coverage. Much will be gained by freeing the present day networks of the constraints imposed by sampling along commercial ship tracks and by the use of XBT technology. The gains to be derived from systematic salinity sampling are harder to quantify because there is no precursor salinity network. However, the lack of background knowledge of the time-varying salinity field makes establishment of the network even more compelling. Salinity variations form a substantial part of density signals in many regions and salinity is a primary diagnostic variable for the hydrologic cycle.

Assuming the global float array is deployed as planned and maintained for at least a decade, its principal achievements will be to:

(1) Obtain an unprecedented dataset for model initialization, data assimilation and dynamical consistency testing of the next generation of global ocean and coupled models.

(2) Enable realistic operational real-time global ocean forecasting for the first time.

(3) Produce an accurate global climatology, with error bars and statistics of variability and valid for the specific period of the array, of monthly mean temperature and salinity as a function of depth.

(4) Produce accurate time-series of heat and freshwater storage (globally) and of the temperature/salinity structure and volume of the world's intermediate and thermocline water masses.

(5) Provide large-scale constraints for atmospheric model-derived surface heat and freshwater fluxes.

(6) Complete the global description of the mean and variability of large-scale ocean circulation, including interior ocean mass, heat and freshwater transport - the equivalent for large-scale ocean circulation of a real-time synoptic upper ocean WOCE.

(7) Determine the dominant patterns and evolution of interannual variability in temperature and salinity, e.g. for analysis of coupled modes of air/sea interaction. Discover other ENSO-like phenomena in the global oceans and their impact on improvement of seasonal-to-interannual atmospheric forecasts.

(8) Provide global maps of the absolute height of the sea surface, with accuracy of about 2 cm on periods of a year and longer – allowing Jason(altimeter)/Argo combinations to examine a broad range of space- and time-scales.

(9) Enable the interpretation of (altimetric) sea surface height by determining the statistical relationship between sea surface height and subsurface temperature and salinity variability.

(10) Directly interpret sea surface height anomalies - for example due to global sea level change, El Nino, etc. – by separating them into contributions due to the effects of (i) E-P, (ii) differential heating and cooling, (iii) advection of heat and freshwater, and (iv) wind-driven redistribution of mass.

3 - IMPLEMENTATION OF ARGO

Argo is now entering its initial implementation phase, including pilot float deployments and data system development as well as further instrumentation development and array design studies. Pilot deployments of Argo floats are presently funded or proposed in Australia, Canada, France, Germany, Japan, the U.K., the U.S.A. and the European Union. Identified regions for funded pilot deployments include the eastern Indian Ocean (Australia, 1999), tropical North Atlantic (U.S.A., 2000), northeast Atlantic (France, 2000) southeast Pacific (U.S.A., 2000). It is planned that the global array will grow from these and other pilot arrays.

Full-scale Argo deployment, with more than 700 floats per year entering the ocean, may occur as early as 2001. An array with global scope (but large gaps remaining) is expected by 2003, in parallel with the beginning of the Global Ocean Data Assimilation Experiment (GODAE). A complete Argo array will be in place by 2005. The principal issues for full Argo deployment are the total number of floats committed to the program and the commitments for deployment in remote ocean regions.

It is recognized that initial national interests are focused on coverage of the Atlantic and Pacific Oceans. Cooperative agreements will be needed to implement a global array, with all nations necessarily contributing to regions outside of their highest priorities. Clearly, the most difficult regions to instrument (Fig 2) will be the Indian Ocean, where about 440 floats are needed, and the Southern Ocean with about 970. Special attention must be directed to building the array in these regions. The Indian Ocean has relatively little sampling in the present upper ocean thermal network, but it is expected that increased observations there will lead to substantial improvements in seasonal to interannual prediction. The Indian Ocean's uniqueness, deriving from strong monsoon forcing, provides another rationale. The Southern Ocean is the least sampled part of the global ocean. It is known to have large interannual climate signals that have not been adequately described. Indeed, even the annual cycle there is poorly known. The benefits of a Southern Ocean Argo array are more exploratory in nature than for the tropics and mid-latitude oceans, but the need there is equally compelling.

4 - TECHNICAL ISSUES FOR ARGO

Communications

Present work is with ARGOS and ORBCOMM communications, plus testing of global cellular networks as a possible future option. In addition to cost, issues related to communications are:

Data quantity: Requirements are 2 kilobytes per profile (compressed), allowing temperature and salinity precision of .001 at 2 m intervals from 0 to 500 m and 5 m intervals from 500 to 2000 m.

Time spent on the sea surface: The target is 30 minutes or less. Minimizing this time will lower risk to the instrument and its sensors (i.e. bio-fouling) as well as decreasing the displacement of the float by surface currents.

Power consumption: The target is for communications to consume less than 10% of the energy budget per cycle (or < 1kJ).

It is not possible presently to focus on a single communications system, as several have the potential to meet requirements in the near future. Additional tests and deployments with ARGOS and ORBCOMM systems are planned in the next year.

Salinity

It is recognized that the development of stable salinity sensors for four-plus year missions is the most difficult technical issue for Argo. Present work focuses both on determining the long-term capabilities of present sensors and on development of better ones. There are now many examples of one and two-year records from profiling floats in the Atlantic, providing stable salinity data (e.g. Fig 3) and using sensors from two different manufacturers. The adoption of 2000 m as the target for profiling depth in Argo provides water masses over most of the global ocean with sufficiently stable T/S to use as a salinity standard. While the detection of T/S variability in mid-depth water masses might one day be an objective for profiling floats, the initial deep sampling will provide a primary calibration check.

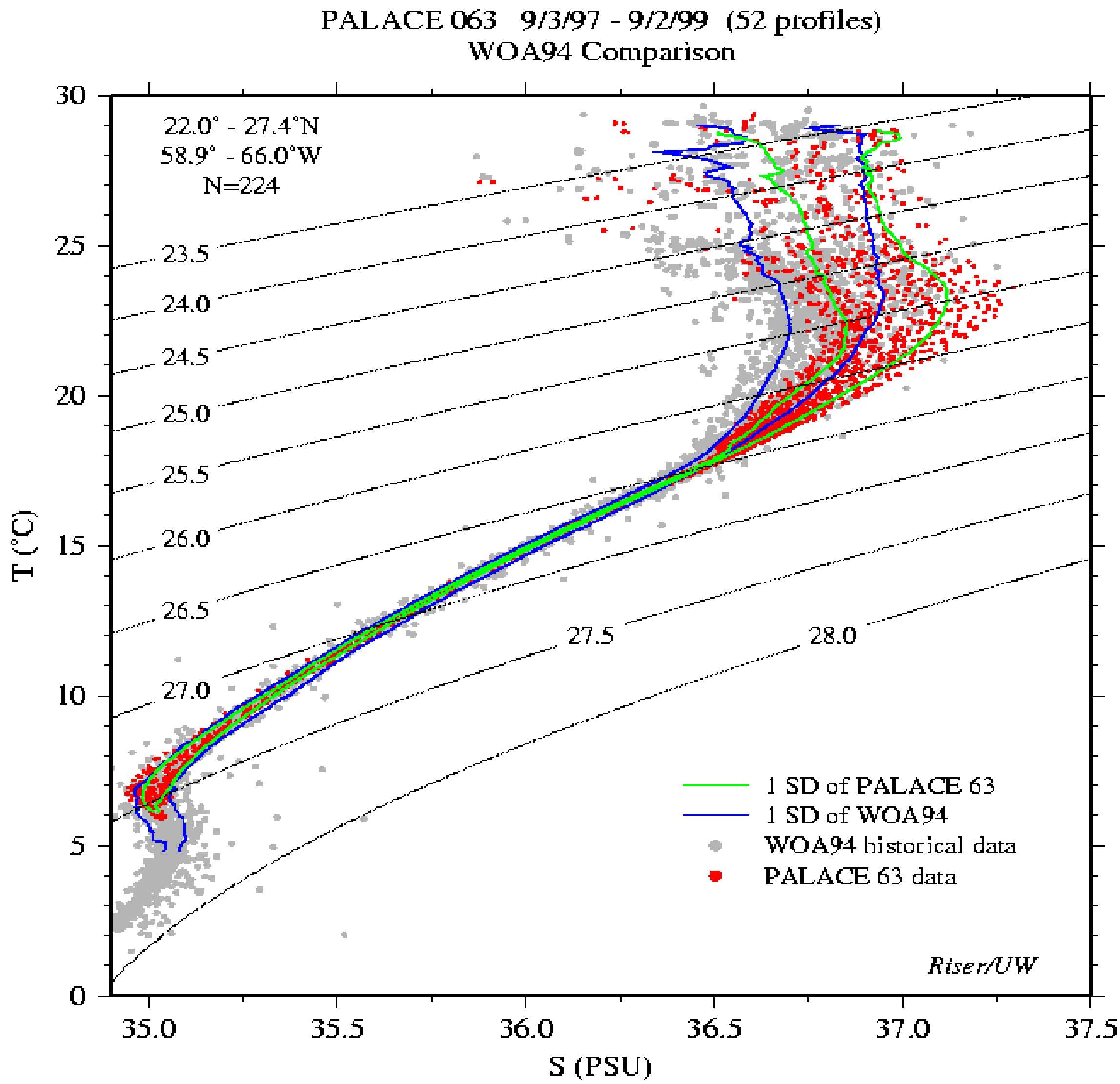

Fig 3: Temperature/salinity values (raw values, red dots) from a float operating in the Sargasso Sea for 2 years. Measured T/S variability is small (< .01 psu) in the thermocline, where natural variability is also small, indicating little or no drift in the salinity sensor.

The main cause of salinity drift is bio-fouling. Technical solutions for control of bio-fouling involve combinations of anti-fouling chemicals, isolation of sensors during the long periods between profiles, and use of redundant sensors for identification of problems. There are several very promising avenues of development. At this point, the most substantial barrier is simply the long time required to test and to demonstrate progress.

Energy use

Considerable progress has been made recently in lowering energy requirements, with improvements due to use of efficient single stroke pumps and better energy use in communications. Energy budgets for SOLO, APEX and PROVOR floats indicate in all cases that battery lifetime of 200 profile cycles to 2000 m profile depth is feasible. The gains in energy efficiency have had two major impacts on experimental design – enabling deeper profiling for salinity calibration checking, and increasing the profiling frequency to a profile per 10 days without compromising float lifetimes.

Deployment technique

Argo floats will be deployed by Volunteer Observing Ships (VOS), aircraft, and research vessels. VOS deployments have been successfully implemented and aircraft deployment has recently been demonstrated. Dedicated use of research vessels will be minimized due to high cost, but research vessels with planned trips to remote regions may be very useful. The distribution of XBT and MET reports demonstrates that much of the ocean is accessible from VOS, with dispersion of floats by mean and time-varying flows an effective means of filling gaps between VOS routes. The efficiency of float dispersion by the flow field is demonstrated by Fig 4, showing the initial positions of all WOCE floats together with their most recent or final positions. The WOCE floats were deployed from widely spaced research vessel tracks, drifting for several years at about 900 m depth. Additional studies are needed of the relative efficiency of VOS deployment/dispersion versus aircraft deployment for achieving optimal float distribution.

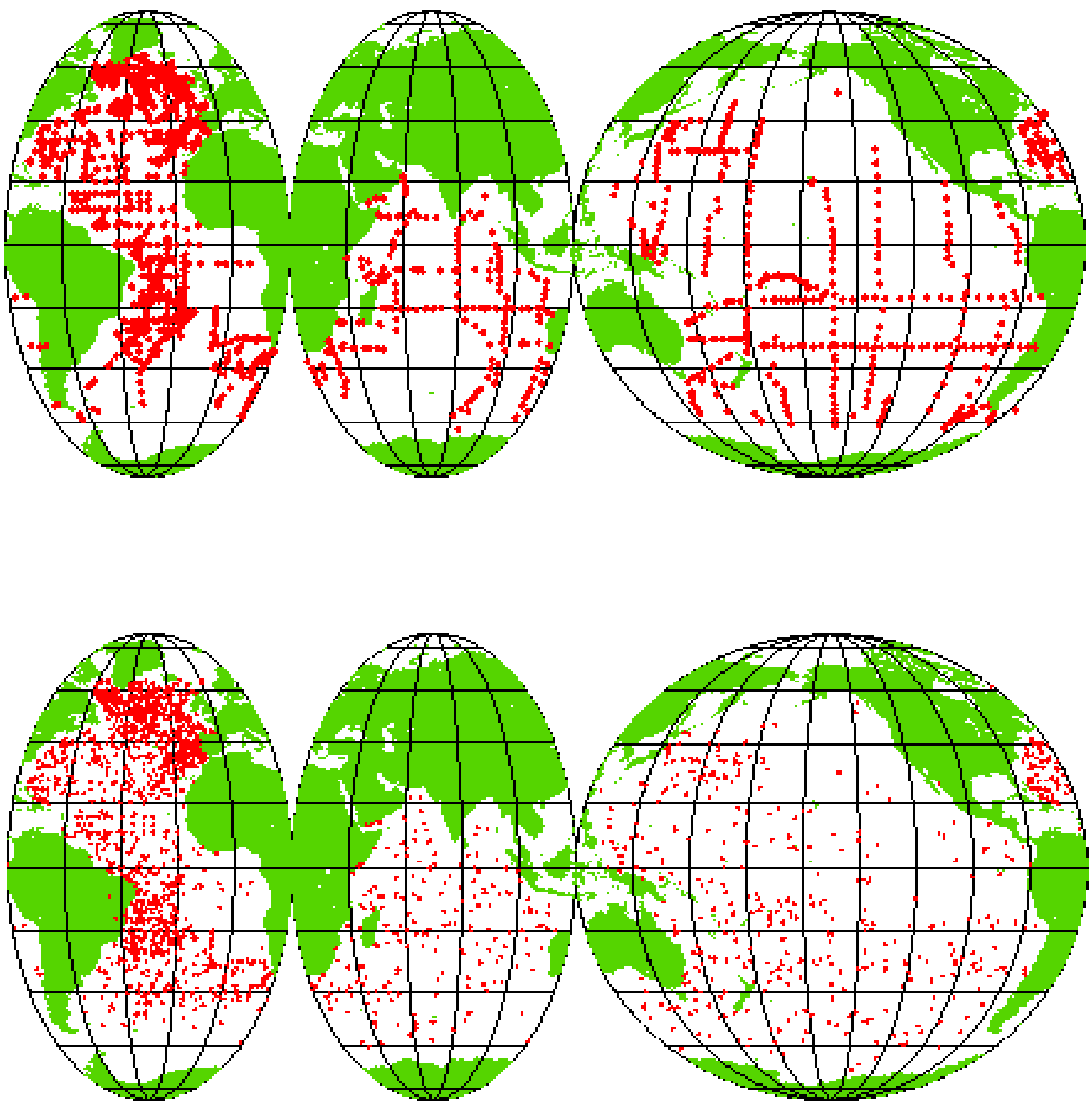

Fig 4: Initial (top panel) and final or most recent (bottom panel) position of all floats deployed in WOCE. Floats deployed along widely spaced lines tend to fill in areas between the lines through random dispersion by the flow field. (Figure courtesy R. Davis)

The choice of parking depth - the depth at which a float drifts between profiles - has impacts on deployment efficiency, on susceptibility to bio-fouling, and on scientific objectives related to observing ocean circulation. The new generation of floats can park at one or more depths, and the parking depth is chosen independently of the profile depth. Deeper parking will produce less dispersion away from initial deployment sites and less bio-fouling of salinity sensors. Shallow parking in the thermocline may be desirable to enhance dispersion away from deployment tracks or for determining flow trajectories at that level. Because of these tradeoffs, it is recognized that no single choice of parking depth is possible for the global array. However, we reiterate that deep profiling is a requirement and 2000 m is the present target for profiling depth.

5 - THE ARGO DATA SYSTEM

The Argo Data System (Fig 5) will evolve from the present Upper Ocean Thermal Data Centers so that it can be inclusive of all forms of real-time upper-ocean temperature and salinity profile data. It is recognized, however, that quality control of salinity data is much more difficult than temperature alone, so this evolution is a major step. For salinity quality control, partnerships between data centers and float/salinity experts are needed. Participation by scientists in the data system should be explicitly included in Argo resource requirements.

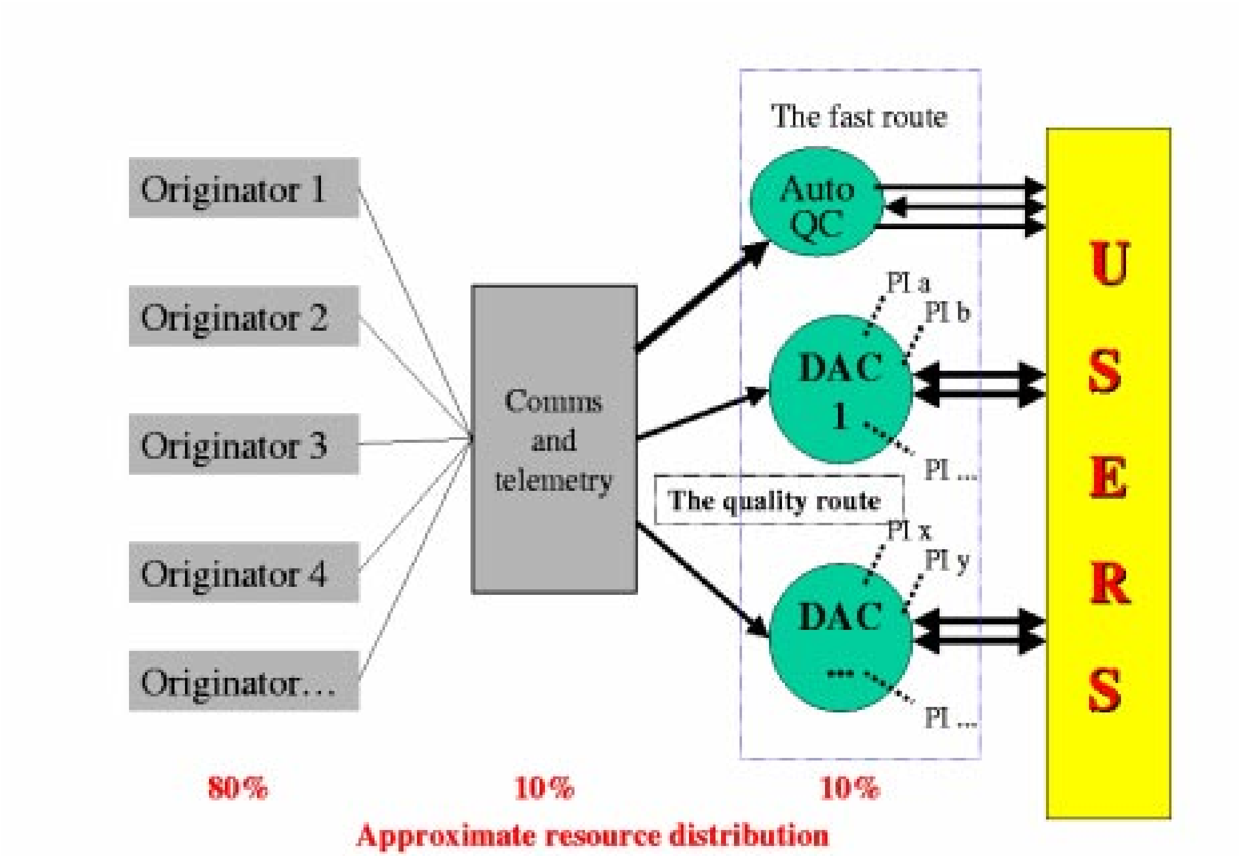

Fig 5: Schematic of the Argo data system. Data follows a fast pathway to operational assimilation and prediction centers and a slower route with more complete quality control for scientific analyses.

Argo data will be publicly available through two pathways (Fig 5) – a near real-time path via the GTS for operational modeling and forecasting and a slower path for scientific applications requiring the best attainable data quality. The elements of the dual-pathway data system are as follows.

Data transmission

Data transmission will be via satellite, with profiles received at data centers within a few hours of collection. This system yields large advantages over present VOS XBT networks both in timeliness of data and in the assurance that appropriate identification information and meta-data are attached to profiles.

Real-time quality control (QC)

The real-time QC procedures must be fully automated and carried out on a 7-day per week, 24-hour per day basis. The objective is to make data available to operational users within 12 hours of collection. Procedures may consist of statistical tests of temperature and salinity and their vertical gradients against climatological data, comparison of profiles with previous data from the same instrument, plus platform speed and checksum tests. Salinity checking will use assumptions of vertical density stability and of limits on deep T/S variability. Real-time QC will include flagging of outlier values and possible recalibration of salinity.

Data tracking

Once collected it is essential to ensure that data get to users. For the global XBT network, a set of "pipelines" define the path of data from VOS to user. Taps are placed in the pipeline at strategic locations. Data counts are made at the taps and discrepancies are noted. When differences are greater than some predetermined values, causes are determined and problems remedied. With Argo data, a somewhat more sophisticated tracking system is possible. A unique tag is associated with every profile and the time and location of each profile is anticipated by the data system. The existence or lack of valid profile data is used to monitor the status of each instrument and to update a master profile inventory.

Delayed-mode QC

Delayed mode QC is required to ensure that a scientifically reviewed data set of highest quality is available to present and future researchers. In this process, it is necessary to use as much upper ocean temperature and salinity data as possible. Individual float profiles must be compared with neighboring floats as well as XBT, XCTD and TSG data to generate products for comparison. For example, temperature maps using neighboring floats and XBTs can be used to identify outliers. Another essential element of delayed-mode QC is examination of sequences of profiles from individual instruments by a scientist, using information from the history of each instrument as well as from nearby instruments. Completion of delayed-mode quality control should occur within a few months of data collection.

Evaluation of the data

Operational forecast centers are a primary user of Argo data so the acceptability of profile data in assimilating models is an important form of evaluation. Data that are not usable in assimilation will be reviewed to determine if the problem is likely to be in the instrument or the assimilation. If the problem is in the data, solutions at the data collection end will be implemented. If the problem is with the assimilation system, revisions in the procedure are needed. This last step in the data system ensures maximum usefulness of Argo data.

6 - INTERNATIONAL ISSUES

Argo is inherently international in its inception and implementation. Formally, it is an element of the Global Climate Observing System/ Global Ocean Observing System (GCOS/GOOS). Argo is the primary *in situ* data-gathering component of GODAE and it is strongly endorsed as part of the Climate Variability and Predictability (CLIVAR) experiment of the WCRP. All nations will have immediate and equal access to Argo data and all will benefit from the resulting improvements in regional and global climate observation and prediction. Argo has received strong international support, and the continuation of that support is expected and essential.

International participation in Argo can take on a number of forms. Float production is technically difficult and expensive, so the burden of production or procurement of floats may fall on a small number of nations having strong interest and necessary resources. Presently, float-producing nations are the U.S.A. and France. However, with the recent open availability of the design for the Scripps SOLO float, interested countries, institutions or companies may obtain state-of-the-art profiling float technology. Participation in Argo by many nations is strongly encouraged, if not via float production or procurement then through logistical support for float deployments and in establishment of regional analysis, assimilation and prediction centers. Expressions of interest are welcomed by the Argo Science Team (www-argo.ucsd.edu).

The existence of a comprehensive data system including float tracking and inventories makes it feasible to monitor the Argo array in real time. One aspect of array monitoring will be to identify and correct gaps in global sampling. This will be a responsibility of the Argo Science Team, drawing on the priorities and commitments of participating nations to fill gaps in a timely manner. A second aspect of array monitoring is to address the possibility of random float entry into 200-mile Exclusive Economic Zones (EEZs). At the recent meeting of the IOC Assembly in Paris, this issue was addressed in the passage of a resolution stating “concerned coastal states must be informed in advance through appropriate channels” if it appears that a profiling float will drift into its EEZ. It was agreed that the Argo Data System would include provisions for interested parties to check on all float positions as well as to see the resulting profile data.

Argo is a unique undertaking for oceanography. It is a multi-national partnership of scientists, government agencies and private industry, formed to produce a global dataset for immediate release to a broad community of users. Participating scientists include the world’s experts in these technologies, giving their expertise to the project while placing the group objectives above individual science. The scope and completeness of the global array, and the rapid public delivery of high quality data are the driving motivations. The result will be a dataset of enormous value both in its immediate uses and in its long-term legacy in the data archive.

7 - CONCLUSION

There is now a broad international consensus that the deployment of a global array of profiling floats is a high priority in the integrated ocean observing system. The scientific and operational objectives are compelling. For the first time, the technology exists to implement global *in situ* observations that are the subsurface counterpart of the remotely sensed satellite networks. The Argo array will provide the capability to knit together many regional components of the ocean observing system and will provide the global broad-scale context for it. Assimilation techniques and computing resources are available to combine the remotely sensed and subsurface datasets for ocean state estimation and prediction. The undertaking is an ambitious one, requiring a major commitment of resources over a sustained period of time. It is unprecedented in the field of oceanography. An international partnership is being built that includes academic and government scientists and operational agencies with the combined abilities and resources to put the array into the water and produce a high quality near real-time data stream. Additional linkages must be built to ensure the rapid utilization of Argo data and the worldwide dissemination of analyses and forecasts for the benefit of mankind.

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